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Optical network unit-based traffic prediction for Ethernet passive optical networks

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Abstract: The authors propose a novel traffic prediction method for the minimisation of packet delay in Ethernet passive optical networks. The method relies on traffic monitoring at the optical network units (ONUs) and utilises readily available traffic information to predict the accumulated burst size of each respective ONU in the following cycle. They demonstrate that a significant delay enhancement can be accomplished by reporting the predicted, rather than the current, burst size to the optical line terminal (OLT). The author's simulation results show that a delay improvement of over 25% can be expected by the proposed method without modifying the well-established interleaved polling scheme with adaptive cycle time dynamic bandwidth assignment scheme at the OLT.

1 Introduction

Passive optical networks (PONs) [1, 2] are an important option for the deployment of future broadband access networks because of their low implementation cost, simple operation and high-line rates that are enabled by the capacity of optical fibers. Contemporary Ethernet PONs (EPONs) and their gigabit PON (XGPON) [3] counterparts have been standardised at line speeds of 10 Gb/s, while upcoming standards are expected to increase the available capacity by a factor of four to ten. EPONs, in particular, enable the convergence between Ethernet, which finds widespread application in local and metro area networks, and the fibre infrastructure that is being installed within the scope of fibre-to-the-home, building and curb end-user access.

In contrast to XGPONs, which emphasise on strict timing and synchronisation for the purposes of real-time traffic transport (especially voice), EPONs are mainly designed for data communications. Within this context, an interleaved polling scheme with adaptive cycle time (IPACT) [4, 5] is implemented at the optical line terminal (OLT) to periodically receive bandwidth requests from all connected optical network units (ONUs) and allocate transmission slots accordingly. The average cycle time in IPACT contributes to the PON system latency, since ONUs are served in a round-robin fashion and each ONU must wait for the full cycle duration before being served again. Thus, the average cycle time and therefore the latency, depends on the bandwidth allocation scheme implemented by IPACT that is utilised at the OLT. In general, bandwidth allocation schemes can be categorised as fixed or dynamic. Fixed bandwidth allocation schemes [6] utilise equal size time-slots and offer a fixed time-slot to each ONU irrespective of its traffic load. The ONU-to-OLT (upstream) communication channel is therefore occupied even when the ONU traffic is not sufficient to fully utilise the slot and this bandwidth underutilisation leads to transmission gaps and increased frame service times. On the other hand, dynamic bandwidth allocation (DBA) [7, 8] assigns the bandwidth in an adaptive fashion based on the traffic load of each ONU. The underlying idea in DBA schemes, such as the one implemented in IPACT, is to re-distribute bandwidth from light-load to heavy-load ONUs within a single cycle duration and consequently fully utilise the available capacity, thus reducing the average frame service time and the overall PON latency.

A further improvement on the PON latency can be obtained by means of traffic prediction, a technique that has been widely studied in both wireline and wireless networks for the purposes of energy conservation [9, 10], quality of service (QoS) provisioning [11, 12] and network control [13, 14], among other areas. Within the framework of PONs, latency can be reduced if an estimate of the expected ONU load (rather than the current value) is used by the DBA of the OLT in the bandwidth allocation process [15]. Since cycle times in IPACT can amount to a few ms, the bandwidth requests that are reported by the ONUs and considered by the DBA may be outdated and not include frames received during the reporting and bandwidth assignment process. The aforementioned frames will experience an additional delay of at least one cycle depending on the PON load, unless a traffic prediction scheme is implemented at the OLT or ONUs to inform the DBA about the estimated frame arrivals. OLT-based traffic prediction relies on estimating future 'on-average' bandwidth requirements for all ONUs based on their previous bandwidth requests. A key drawback of OLT-based prediction, however, is that it may not accurately identify, and therefore respond, to rapid changes in the ONU traffic, since prediction is performed on time-scales equal to several cycles. ONU-based prediction, on the other hand, can be performed within a single cycle, since ONUs are able to constantly monitor incoming traffic, and therefore can adapt to traffic changes significantly faster.

Within this context, we propose a novel ONU-based traffic prediction method for decreasing latency in EPONs. The method estimates (a) the frame arrival rate within the duration of a single cycle and (b) the duration of the upcoming cycle. Subsequent, the two quantities are combined to produce the amount of data that the ONU will have accumulated at the arrival of the next GATE message from the OLT, which informs the ONU when and for how long to transmit. The ONU then transmits a request (REPORT) message that carries this bandwidth estimate for the next cycle, thus providing the DBA mechanism with more up-to-date traffic requirements. We show via simulation that the proposed prediction method can reduce the frame delay up to over 25% as compared with non-predicting IPACT alternatives (limited and gated), depending on the traffic load and the burstiness of the incoming traffic. We also show that this method is 'fair' in the sense that all ONUs receive the same bandwidth on average, regardless of their distance, and that it does not waste capacity because of erroneous prediction, that is, the network has the same throughput as in the case without prediction. Furthermore, the proposed method is fully compatible with the existing EPON multi-point control protocol (MPCP) [8], since it uses the standard REPORT and GATE messages to communicate bandwidth requirements and assignments between the OLT and ONUs, and it is also transparent to the DBA (IPACT in our experiments) that is implemented at the OLT.

The rest of this paper is structured as follows. Section 2 describes previous works on OLT and ONU-based traffic prediction and discusses potential benefits of the proposed method over existing techniques. Section 3 presents the proposed traffic prediction technique and its scope of application in EPONs. Section 4 details the simulation setup that was utilised to evaluate the performance of the method and discusses the results that have been obtained in terms of latency, fairness and throughput. Finally, Section 4 summarises the main contributions of this paper.

2 Related work

A large variety of traffic prediction algorithms for EPONs have been proposed in the last years, in order to improve the bandwidth allocation strategy and PON networks' capabilities. DBA without traffic prediction, such as the limited bandwidth allocation (LBA) scheme was studied in [4, 7, 16]. In these techniques, the maximum time-slot length $B_{\max}$ of each ONU in a cycle is upper bounded. The drawback of LBA scheme is that the maximum bandwidth, which can be assigned to the ONU's is $B_{\max}$, even if additional bandwidth is required, leading to poor utilisation and increased packet delay in the upstream direction. To address this, predictive schemes that measure the aggregated traffic are used to update the allocated bandwidth and improve total system performance [8, 17]. Service prediction techniques follow in general a common procedure for estimating Ethernet data in the PON. Typically a predictive technique establishes a mathematical model that processes the series of data packets to predict the future traffic flow. These prediction techniques can be applied to different parts of the network: at the OLT [18, 19] or at the ONUs [5, 20, 21].

The technique proposed in [18] consists of a two-stage bandwidth request scheme. In the first stage, DBA is performed for the next cycle at the ONU level assigning bandwidth to the ONUs which have more unstable traffic. In that way becomes easier to reduce the prediction error by shortening their waiting times. In the next stage, a linear prediction-based excess bandwidth request is done for the more stable ONUs. At the OLT, the proportionally available bandwidth for an ONU is allocated to related traffic classes, strictly based on their respective requests ordered by their priority. In [19], the authors propose a prediction process that is based on genetic expression programming to reduce the queue size variation and the packet delay. Taking a different approach, in [5, 20, 21], the authors propose prediction techniques that are applied at the ONUs. In [5], a limited sharing with traffic prediction scheme was proposed and shown to enhance DBA process by means of traffic prediction. For ONU-based traffic prediction a different approach was presented in [20] where the authors propose a linear class-based prediction model, which tries to estimate the incoming traffic until the next polling cycle. This model uses information from previous bandwidth requests in order to predict bandwidth request at each ONU in the network, according to the OLT priority classes. The effect of long-range dependence of internet traffic in the prediction was studied in [21].

Although the prior works have used complicated prediction techniques at the ONUs, they predict a single parameter that is the bandwidth to be allocated, which is, however, a complex metric (ratio of data size over duration). We use two different techniques that are, however, linear and simpler when compared with prior work to predict the constituent parameters of bandwidth, namely the cycle duration and the data size accumulated during the related period with the goal of obtaining better or at least equal accuracy at less complexity. Note that the complexity of the employed prediction scheme is particularly important, since this scheme is executed at the ONUs, required to have low computation power to maintain a low cost. In particular, we use the normalised least-mean-square (NLMS) and the mean-square-error (MSE) methods [22] to predict the time appearance of the next GATE message and the ONU's queue size just before that message. As it will be demonstrated by the simulation results, the proposed algorithm achieves significant delay reductions in comparison to IPACT without any noticeable effect on the network throughput.

3 ONU-based traffic prediction algorithm

In the standard EPON operation, the communication between the OLT and the ONUs takes place by means of an IPACT. IPACT operates in successive cycles and during each respective cycle the OLT sends GATE messages that carry bandwidth grants to all ONUs in the EPON. The ONUs respond to the GATE messages and send their data in a co-ordinated fashion, as specified in the GATE messages, so as to achieve collision free transmissions in the upstream direction. In addition to their data, ONUs also inform the OLT about their bandwidth requirements (buffer sizes) via REPORT messages and the IPACT cycle ends upon the reception of the REPORT messages from all ONUs in the EPON. At that time, the OLT executes a DBA algorithm to calculate the grants of the next cycle, and a new exchange of GATE and REPORT messages ensues.

Following the communication scenario presented above, the REPORT messages carry bandwidth requests that are only utilised by the DBA at the end of a cycle. As a result, the DBA does not take into account (a) data that have been accumulated at ONUs that are served near the beginning of the cycle and are forced to report early, or (b) data that will be accumulated at ONUs that are served towards the end of the upcoming cycle and will receive a late grant. This leads to an additional delay of a cycle time, which can be particularly important in IPACT varieties with increased or infinite maximum cycle durations. Still, the additional delay can be reduced if the DBA takes into account the future ONU buffer sizes rather than the current. This can be implemented in a straightforward manner by having each ONU perform a prediction about its buffer status for the instant it receives the next GATE message exactly before the generation of the current REPORT message. The ONU can then use the REPORT message to communicate the prediction to the OLT rather than the actual buffer size.

Our proposed prediction algorithm of the ONU buffer size is based upon the last observation and can be summarised as follows (refer to Fig. 1):

- *Step 1*: Constantly monitor the incoming traffic from hosts in a log file until a GATE message has been received from the OLT.
- *Step 2*: Upon the reception of the GATE message keep record of its arrival time $T(n-1)$.
- *Step 3*: Utilise the traffic log to estimate the instantaneous buffer size $B(t)$.
- *Step 4*: Combine $B(t)$ and $T(n)$ to calculate the expected buffer size $B(n)$ at the reception of the next GATE message.
- *Step 5*: Utilise the arrival times of previous GATE messages to predict the arrival time of the next GATE message $T(n)$.
- *Step 6*: Transmit the allocated number of frames and then issue a REPORT message that carries the bandwidth request $B(n)$.
- *Step 7:* Reset the traffic log to the remaining buffer size and re-start from Step 1.

The presented algorithm requires the estimation of two key parameters, namely: (a) the instantaneous ONU buffer size $B(t)$, and (b) the arrival time of the next GATE message $T(n)$. The estimation of the instantaneous buffer size is performed by monitoring the incoming frames that arrive between REPORT messages. To this end, the ONU creates a log of the frame size S_i and the arrival time t_i for each frame that is received. Each frame arrival corresponds to an increase of the number of bytes B_i that are stored at the ONU buffer, following

$$B_i = B_{i-1} + S_i \tag{1}$$

while the remaining queue size B_0 after the ONU transmission is used to initialise (1). A linear regression equation between the buffer size $B(t)$ and the elapsed time t is then calculated by the (t_i, B_i) pairs, according to

$$B(t) = r \cdot t + c \tag{2}$$

where parameters r and c are calculated in a least-mean-squares fashion as

$$\begin{aligned} c &= \frac{\sum_{i=1}^{N} t_i^2 \cdot \sum_{i=1}^{N} B_i - \sum_{i=1}^{N} t_i B_i \cdot \sum_{i=1}^{N} t_i}{N \cdot \sum_{i=1}^{N} t_i^2 - \left(\sum_{i=1}^{N} t_i\right)^2} \\ r &= \frac{N \cdot \sum_{i=1}^{N} t_i B_i - \sum_{i=1}^{N} B_i \cdot \sum_{i=1}^{N} t_i}{N \cdot \sum_{i=1}^{N} t_i^2 - \left(\sum_{i=1}^{N} t_i\right)^2} \end{aligned} \tag{3}$$

assuming that an arbitrary number of N frames have arrived between successive REPORT messages. The traffic monitor log is reset after each REPORT so that the traffic estimation of previous cycles does not affect future estimations; in this fashion, the ONU can adapt to rapid variations in its traffic load and inform the OLT, accordingly.

Given (2), the ONU is able to predict its queue status at any given future time t and up to the next GATE message. The arrival time of the next GATE message, however, is not known when the ONU creates the REPORT message and as a result the ONU has to estimate it, as well. To this end, the ONU monitors the arrival times of GATE messages and predicts the arrival time of the next GATE $T(n)$ by means of a NLMS prediction filter [19], since GATE messages can be expected in a fairly regular basis that is determined by the average cycle time. Within this context, the arrival time of the next GATE message is estimated as

$$\hat{T}(n) = \sum_{i=1}^{p} w_n(i) \cdot T(n-i) \tag{4}$$

with p being the filter order. The filter co-efficients $w_n(i)$ are updated at every cycle according to

$$\begin{aligned} w_n(i) &= w_{n-1}(i) + M \cdot e(n-1) \\ &\quad \cdot \frac{T(n-i)}{\sum_{k=1}^{p} (T(n-k))^2}, \quad i = 1, \ldots, p \\ e(n-1) &= T(n-1) - \hat{T}(n-1) \end{aligned} \tag{5}$$

where the NLMS step size M has a constant numeric value (Table 1). It then follows from (2) and (4) that the ONU prediction for its buffer size at the arrival time of the next GRANT message can be calculated as

$$\hat{B}(n) = r \cdot \hat{T}(n) + c - B_G(n-1) \tag{6}$$

where $B_G(n-1)$ is the actual bandwidth (in bytes) that has been granted to the ONU at the current cycle.

4 Simulation analysis and results

4.1 Simulation setup

The performance of our proposed algorithm was verified via simulation experiments using the OMNET++ open source simulator [23]. The simulation setup is presented in Fig. 2 and the respective simulation parameters are summarised in

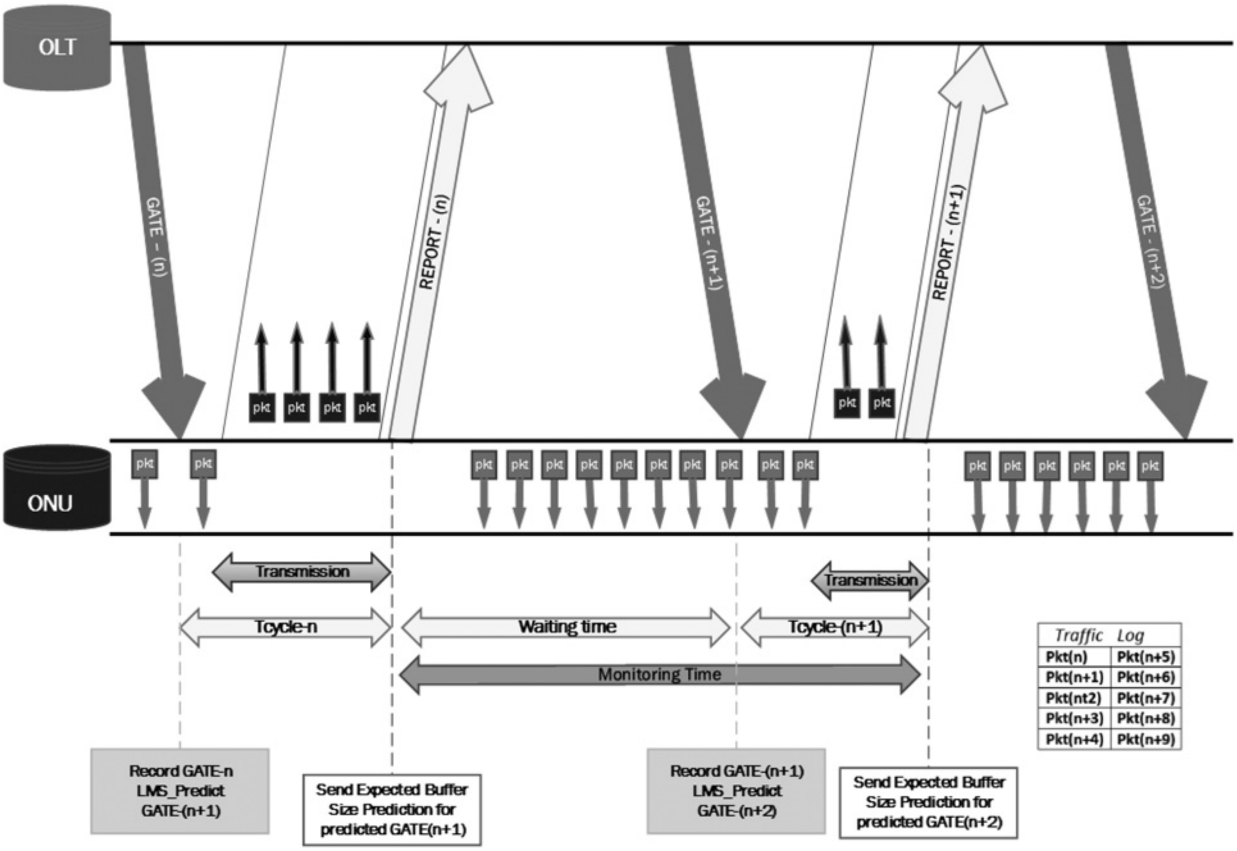

Fig. 1 *Prediction algorithm*

Table 1. In the presented setup, a standard EPON architecture interconnected an OLT with eight ONUs at distances of 10 km, while the EPON rates were considered asymmetric (10 Gb/s downstream–1 Gb/s upstream). Standard MPCP GATE and REPORT messages were utilised to communicate grants and reports between the OLT and the ONUs, as it has been described in the previous section. The communication was based on existing OMNET++ models that provided the basic MPCP functionalities at the OLT and ONUs. Two IPACT DBA principles were implemented at the OLT, namely the ‘Limited’ and ‘Gated’, since other principles perform very closely to the Limited-IPACT in terms of delay, while Gated-IPACT presents the minimum delay of all principles [24]. For the Limited-IPACT implementation, OLT grants $B_G(n)$ were calculated as

$$B_G(n) = \begin{cases} \hat{B}(n) & \hat{B}(n) \le W_{\max} \\ W_{\max} & \hat{B}(n) \ge W_{\max} \end{cases} \tag{7}$$

where $W_{\max}$ is the maximum transmission window size per ONU. $W_{\max}$ was calculated from the maximum cycle time

Table 1 Simulation parameters

	Symbol	Description	Value (Limited-IPACT)		Value (Gated-IPACT)
physical layer parameters	N_{ONU}	number of ONU’s	8		
	N_{host}	number of ONU hosts	15		
	d	ONU distance	10 km		
	R_d	downstream line rate	10 Gb/s		
	R_u	upstream line rate	1 Gb/s		
	R_n	host line rate	100 Mb/s		
IPACT parameters	T_{max}	max cycle time	2 ms		unlimited
	W_{max}	maximum grant size	82.500 bytes		unlimited
traffic parameters	a (a_{ON}, a_{OFF})	Pareto parameter	1.2, 1.5 and 1.8		
	b (b_{ON}, b_{OFF})	Pareto parameter	A	b_{ON}	b_{OFF}
			1.2	0.00000375	0.001495–0.000495
			1.5	0.00000375	0.001493–0.000493
			1.8	0.00000375	0.0016–0.00048
prediction parameters	P	NLMS order	25		
	M	NLMS step size constant	0.0001		

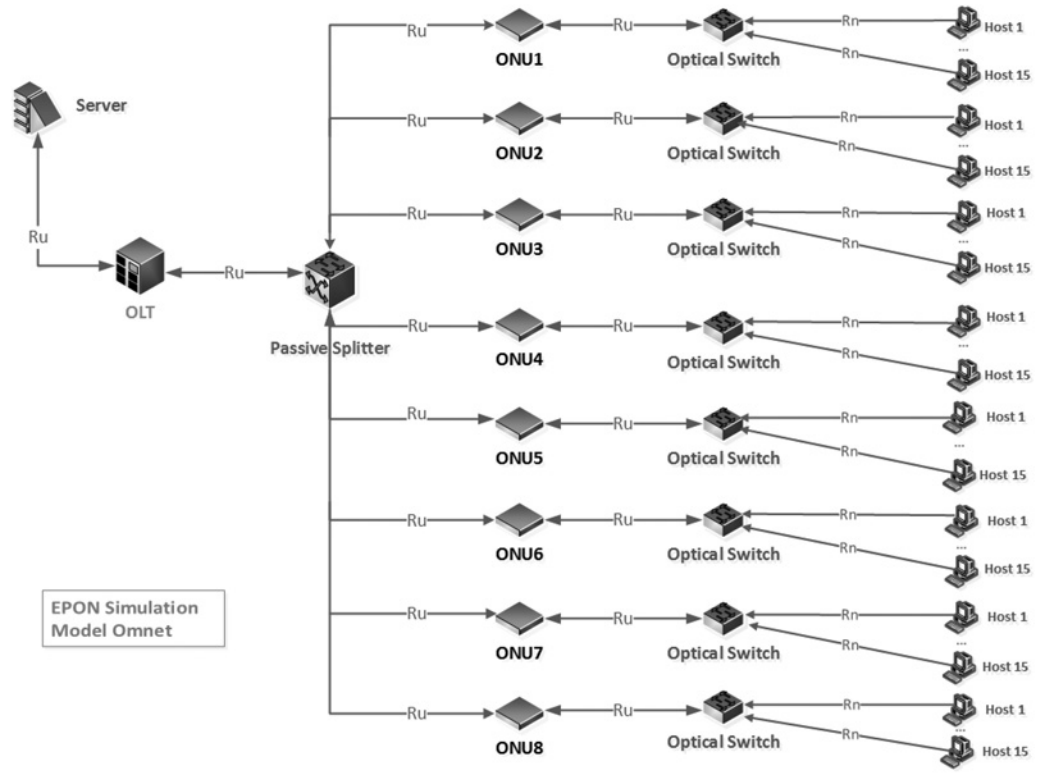

Fig. 2 *Simulation setup*

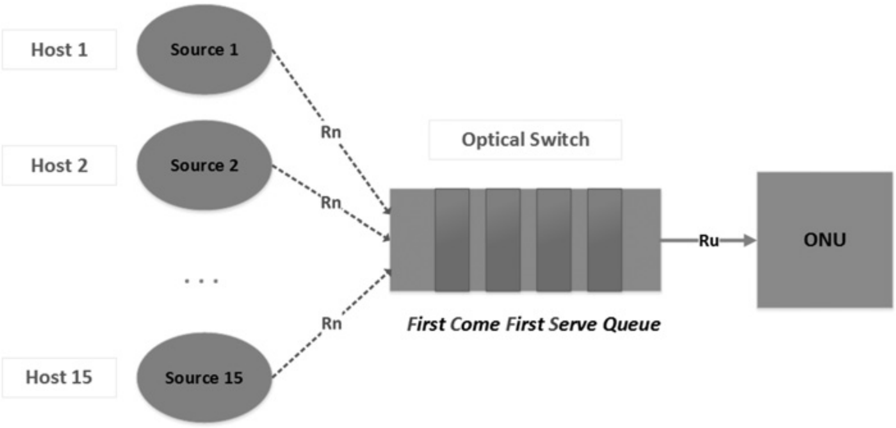

Fig. 3 *Traffic generation model*

$T_{\max}$, the number of ONUs N_{ONU} and upstream burst framing overheads that are required by the EPON standard. On the other hand, Gated-IPACT always allocated the requested bandwidth and the OLT grants were simply given by

$$B_G(n) = \hat{B}(n) \tag{8}$$

As far as the ONUs are concerned, all ONUs monitored incoming traffic and implemented the prediction algorithm that is detailed in Section 3. Incoming traffic was fed to each ONU from an optical switch that aggregated frames from 15 independent hosts (sources), as shown in Fig. 3. For the purposes of this work, hosts transmitted data in the

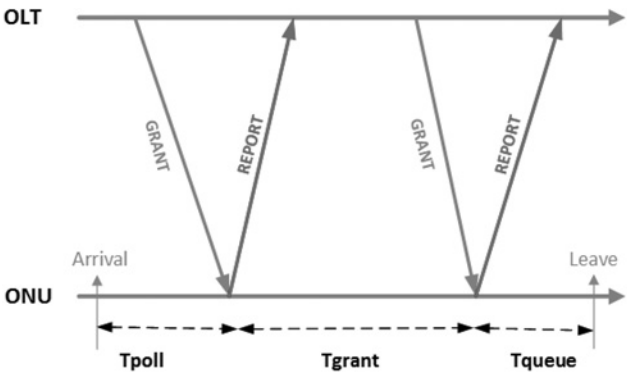

Fig. 4 *Delay components*

form of fixed size 1000 byte Ethernet frames at a line rate R_n of 100 Mb/s. Each host generated frames independently according to an ON/OFF traffic model, where busy (ON) periods were followed by idle (OFF) periods. The ON and OFF periods obeyed Pareto distributions

$$f(x) = \frac{a \cdot b^a}{x^{a+1}} \tag{9}$$

with parameters a and b that relate to the average busy and idle durations, $T_{\rm ON}$ and $T_{\rm OFF}$, respectively, as

$$\begin{aligned} T_{\rm ON} &= \frac{a_{\rm ON} \cdot b_{\rm ON}}{a_{\rm ON} - 1} \\ T_{\rm OFF} &= \frac{a_{\rm OFF} \cdot b_{\rm OFF}}{a_{\rm OFF} - 1} \end{aligned} \tag{10}$$

The Pareto traffic generators were implemented at each host by incorporating in OMNET++ the code segments that are available online [25], [26].

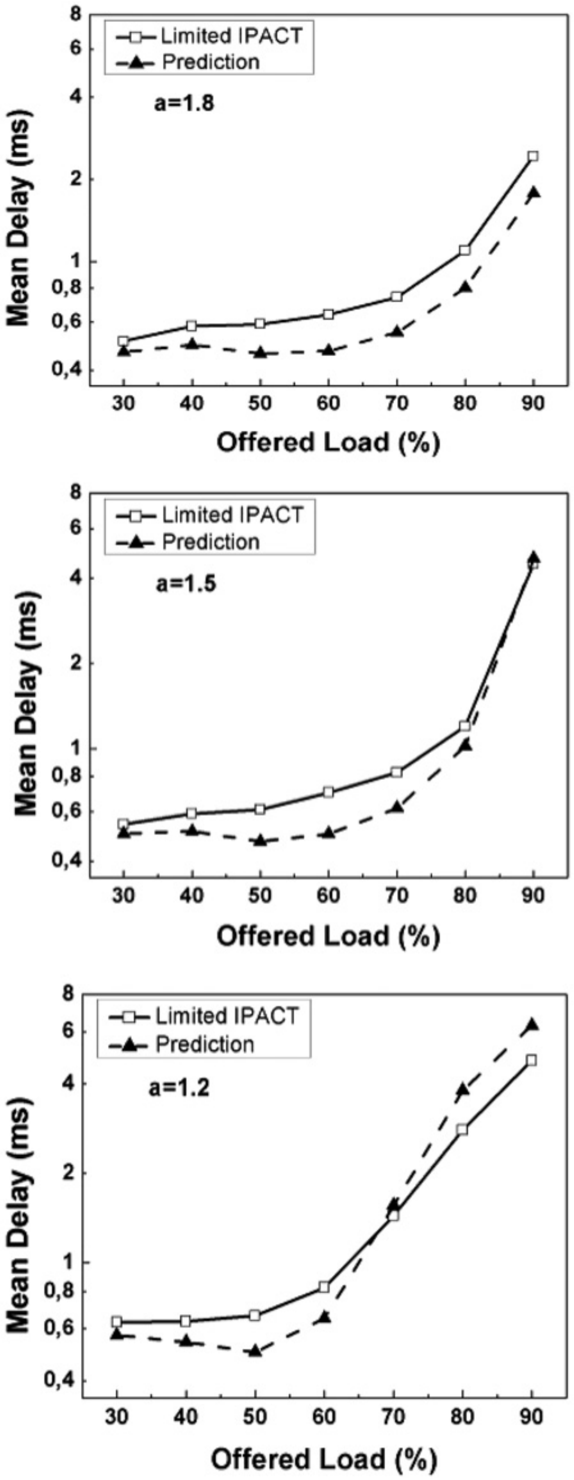

Fig. 5 *Average frame delay against the offered load for Limited-IPACT with and without prediction*

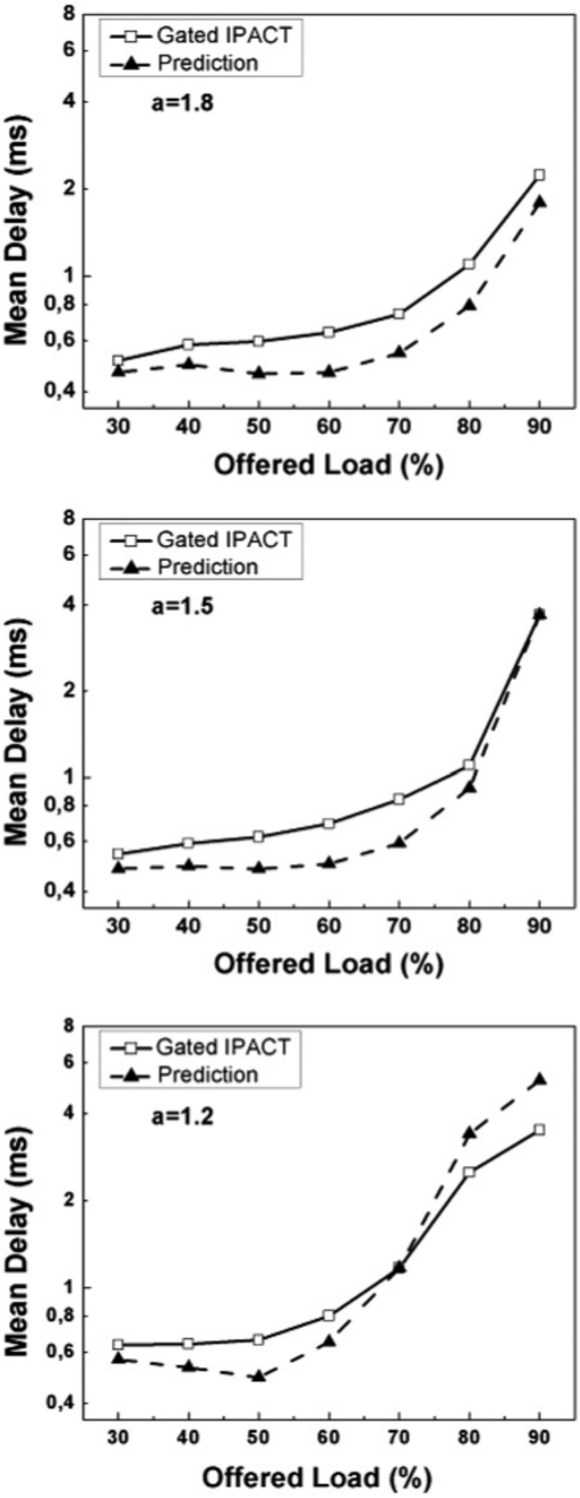

Fig. 6 *Average frame delay against the offered load for the Gated-IPACT with and without prediction*

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The values that were used in our simulations for a_{ON}, b_{ON} and a_{OFF}, b_{OFF} for the ON and OFF periods are also presented in Table 1. These values resulted in ON–OFF periods with durations of the ms time scale, which corresponds to a single IPACT cycle, since an access-oriented PON is not expected to remain idle for several successive IPACT cycles. Given the average busy and idle period duration of each host, it was possible to calculate the offered load ρ in the PON from the number of ONUs (N_{ONU}), the number of hosts per ONU (N_{host}) and the individual host load (ρ_{host}) as

$$\begin{aligned} \rho &= N_{\mathrm{ONU}} \cdot N_{\mathrm{host}} \cdot \rho_{\mathrm{host}} \cdot \\ &= N_{\mathrm{ONU}} \cdot N_{\mathrm{host}} \cdot \frac{T_{\mathrm{ON}}}{T_{\mathrm{ON}} + T_{\mathrm{OFF}}} \end{aligned} \tag{11}$$

4.2 Results and discussion on frame delay

The simulation setup was used to obtain the average delay that frames experience in the ONUs and accounts for the polling, grant and queuing delays that are illustrated in Fig. 4. The respective results are shown in Fig. 5 for the Limited-IPACT with and without the proposed prediction algorithm under three different traffic burstiness scenarios ($a = 1.8$, 1.5 and 1.2). The results clearly demonstrate that the Limited-IPACT performs in a superior fashion when prediction-based reports are sent by the ONUs, especially at low and medium loads where prediction is actually needed. A percentile delay reduction of over 25% is observed for medium offered loads around 0.6, while a smaller benefit is observed as the load becomes lighter. For higher loads, prediction only has a minor beneficial impact when the traffic is relatively smooth ($a = 1.8$ and 1.5). When the traffic becomes significantly bursty ($a = 1.2$), the proposed prediction algorithm can be detrimental in terms of latency, mainly because the cycle durations become irregular and the GRANT arrival times are not correctly calculated by the NLMS. As a result, ONUs request the largest possible grant and IPACT performs in a TDMA manner with maximum duration bandwidth grants.

A similar behaviour is observed for Gated-IPACT, as well, and the corresponding results are shown in Fig. 6. The proposed prediction mechanism further improves the average delay in this IPACT variation and a percentile delay reduction of over 25% is also observed in the simulation results for medium loads. An important difference with Limited-IPACT, however, is becoming evident for bursty traffic ($a = 1.2$) and at heavy loads; in this regime even more extended bandwidth grants are requested by the ONUs and are allowed by the OLT due to the fact that Gated-IPACT does not pose an upper limit on the size of the grants. As a result, the average delay is also significantly increased by a significant factor. Still, this does not mean that prediction-enabled ONUs are wasting network resources. As we demonstrate in the following paragraph, the throughput of both IPACT variations remains the same irrespective of the use of the prediction mechanism.

4.3 Results and discussion on throughput

The same simulation setup was also utilised to assess throughput performance of PON in the presence of the

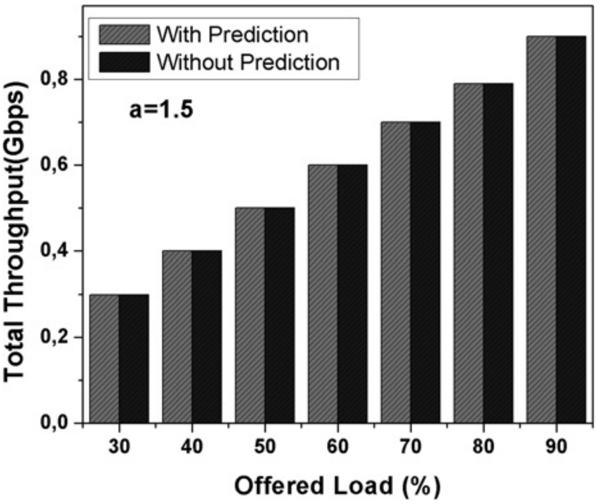

Fig. 7 *Total network throughput against the offered load for Limited-IPACT with and without prediction*

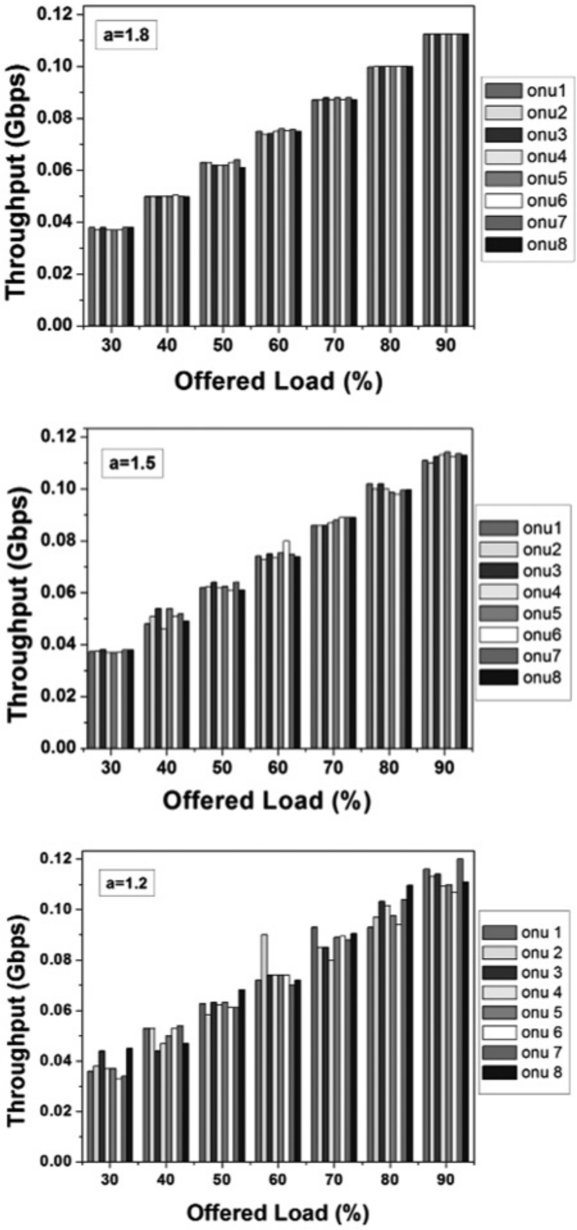

Fig. 8 *Throughput per ONU against the offered load for Limited-IPACT with prediction*

proposed prediction algorithm. Despite the fact that the algorithm has been mainly engineered to decrease latency, it is of importance to also establish its impact on throughput and verify that (a) it allows fair utilisation of the PON bandwidth, in the sense that all ONUs are allocated the same bandwidth on average, and (b) it does not overestimate the bandwidth requirements of ONUs, thus creating idle periods within cycles and lowering the utilised PON bandwidth.

Fig. 7 shows the total PON throughput of Limited-IPACT against the offered load with and without the proposed prediction scheme. It can be verified from the figure that the PON throughput is practically identical for both cases, which serves to establish that our algorithm does not achieve a latency improvement at the expense of unutilised bandwidth. Similar results (not shown for brevity purposes) have been obtained for other values of the a Pareto parameter, as well as the Gated-IPACT simulations. With respect to the level of fairness that is achieved while efficiently serving ONUs, Figs. 8 and 9 demonstrate that the prediction algorithm does not impose significant unfairness. When traffic is relatively smooth ($a = 1.8$ and 1.5) the mean maximum difference in throughput among the ONUs is 2.4% for $a = 1.8$ and 8.5% for $a = 1.5$ for the Limited-IPACT. Similarly, for the Gated-IPACT the differences are 2.5% for $a = 1.8$ and 6.65% for $a = 1.5$. Even when the traffic becomes bursty ($a = 1.2$), the mean maximum differences become high only for specific cases, while their mean value equals 18.5 and 17% for the Limited-IPACT and Gated-IPACT, respectively. Thus, we conclude that the proposed prediction algorithm significantly reduces the mean packet delay without degrading the throughput performance of the PON.

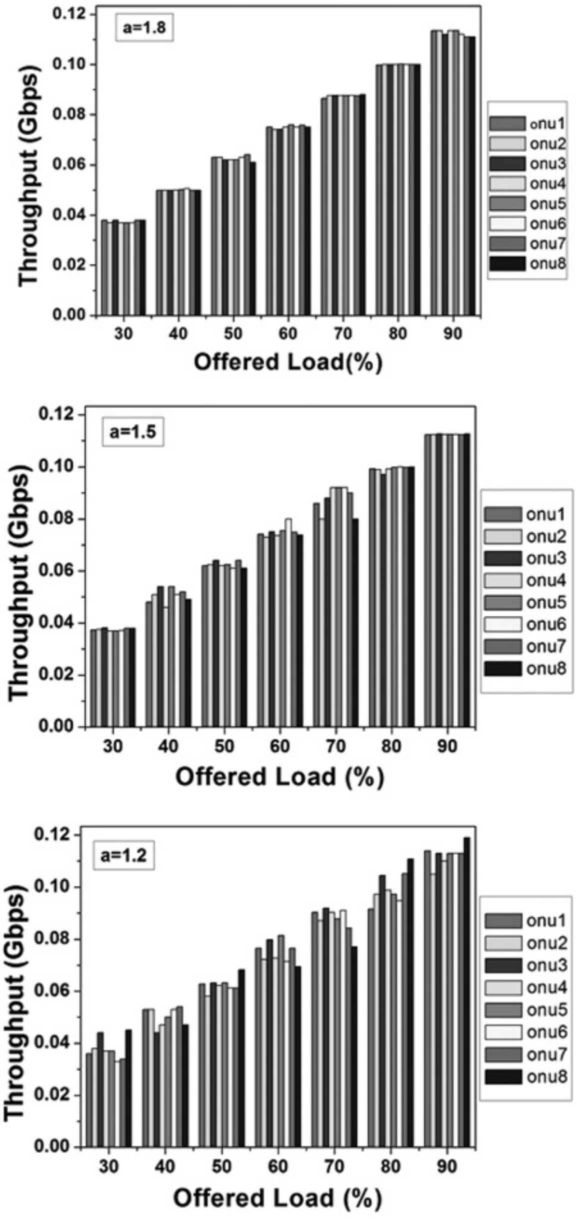

Fig. 9 *Throughput per ONU against the offered load for Gated-IPACT with prediction*

5 Conclusion

We presented an ONU-based prediction method that is applicable in EPONs. The method relies on the application of the MSE and the NLMS algorithms for the estimation of the instantaneous ONU load and IPACT cycle duration, respectively, to predict the ONU buffer size at the time of its next transmission. We showed via simulations that if the predicted size, rather than the actual, is reported to the OLT then a significant (over 25%) average delay reduction can be realised over standard EPON operation without any impact on the throughput. Moreover, the proposed technique is totally compatible with the bandwidth reporting and allocation mechanisms that have been standardised in EPONs, as well as well-known IPACT variations (Limited and Gated).

6 Acknowledgment

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7 References

1 Mukherjee, B.: 'Optical WDM networks', University of California, Davis, (Springer, 2006)
2 Jue, J., Vokkarance, V.: 'Optical burst switched networks series' (Springer, 2005)
3 Effenberger, F.: 'The XG-PON system: cost effective 10 Gb/s access', *J. Lightw. Technol.*, 2011, **4**, (29), pp. 403–409
4 Kramer, G., Mukherjee, B., Pesavento, G.: 'IPACT: a dynamic protocol for Ethernet PON (EPON)', *IEEE Commun. Mag.*, 2002, **40**, (2), pp. 74–80
5 Luo, Y., Ansari, N.: 'Limited sharing with traffic prediction for dynamic bandwidth allocation and QoS provisioning over EPONs', *OSA J. Opt. Netw.*, 2005, **4**, (9), pp. 561–572
6 Kramer, G., Mukherjee, B., Pesavento, G.: 'Ethernet PON (ePON): design and analysis of an optical access network', *Photonic Netw. Commun.*, 2001, **3**, (3), pp. 307–319
7 Kramer, G., Mukherjee, B., Maislos, A.: 'Ethernet passive optical networks', in Dixit, S. (Ed.): 'Multiprotocol over DWDM: building the next generation optical internet' (John Wiley & Sons, 2003), pp. 229–260
8 Mcgarry, M., Reisslein, M., Maier, M.: 'Ethernet passive optical network architectures and dynamic allocation algorithms', *IEEE Commun. Surv.*, 2008, **3**, (10), pp. 46–60
9 Hsieh, J.R., Lee, T.H., Kuo, Y.W., *et al.*: 'Energy-efficient multi-polling scheme for wireless LANs', *IEEE Trans. Wirel. Commun.*, 2009, **8**, pp. 1532–1541
10 Zhu, Z.: 'Design of energy-saving algorithms for hybrid fiber coaxial networks based on the DOCSIS 3.0 standard', *IEEE/OSA J. Opt. Commun. Netw.*, 2012, **4**, pp. 449–456
11 Yoo, S.-J.: 'Efficient traffic prediction scheme for real-time VBR MPEG video transmission over high-speed networks', *IEEE Trans. Broadcast.*, 2002, **48**, (1), pp. 10–18

12 Liang, Y.: 'Real-time VBR video traffic prediction for dynamic bandwidth allocation', *IEEE Trans. Syst. Man Cybern.*, 2004, **34**, (1), pp. 32–47
13 Shu, Y., Jin, Z., Wang, J., Yang, O.W.: 'Prediction-based admission control using FARIMA models'. Proc. of the IEEE Int. Conf. on Communications (ICC'00), New Orleans, 2000, vol. 3, pp. 1325–1329
14 Sang, A., Li, S.: 'A predictability analysis of network traffic'. Proc. IEEE INFOCOM, Israel, March 2000, pp. 342–351
15 Luo, Y., Ansari, N.: 'Bandwidth allocation for multiservice access on EPONs', *IEEE Commun. Mag.*, 2005, **43**, (2), pp. 16–21
16 Kramer, G., Mukherjee, B., Dixit, S., Ye, Y., Hirth, R.: 'Supporting differentiated classes of service in Ethernet passive optical networks', *J. Opt. Netw.*, 2002, **1**, pp. 280–298
17 Sadek, N., Khotanzad, A.: 'A dynamic bandwidth allocation using a two-stage fuzzy neural network based traffic predictor'. Proc. of IEEE Int. Conf. on Neural Networks, Hungary, July 2004, pp. 2407–2412
18 Hwang, I.-S., Shyu, Z.-D., Ke, L.-Y., Chang, C.-C.: 'A novel early DBA mechanism with prediction-based fair excessive bandwidth allocation scheme in EPON', *Comput. Commun.*, 2008, **31**, pp. 1814–1823
19 Hwang, I.-S., Lee, J-Y., Liem, A.: 'QoS-based genetic expression programming prediction scheme in the EPON's'. Progress in Electromegnetics Research Symp. Proc., March 2012, p. 1589
20 Swades, D., Vaibhav, S., Hari, G.M., Navrati, S., Abhishek, R.: 'A new predictive dynamic priority scheduling in Ethernet passive optical networks (EPONs)', *Opt. Switch. Netw.*, 2010, **7**, pp. 215–223
21 Morato, D., Acacil, J., Diez, L.A., Izal, M., Magana, E.: 'On linear prediction of internet traffic for packet and burst switching networks'. IEEE ICCN, USA, 2001
22 Diniz, P.S.R.: 'Adaptive filtering, algorithms and practical implementation' (Springer, 2002, 4th edn., 2013)
23 'Omnet++ simulator', http://www.omnetpp.org/
24 Kramer, G., Mukherjee, B., Pesavento, G.: 'Interleaved polling with adaptive cycle time (IPACT): a dynamic bandwidth distribution scheme in an optical access network', *Photonic Netw. Commun.*, 2002, **4**, (1), pp. 89–107
25 'Generator of self-similar traffic', http://www.glenkramer.com/ucdavis/code/trf_gen3.html
26 Harandi, S.T.: 'Self-Similar Traffic Modeling and Clos-like Packet Switch Architectures', Postdoctoral thesis, University of Ottawa, 2005